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EXPERIMENTS FROM A SMALL PROBE WHICH ENTERS THE ATMOSPHERE OF MARS

by R. A. Hanel, L. E. Richtmyer, R. A. Stampfl, and W. G. Stroud

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SUMMARY

In the long-range national space program for this decade, Mars and Venus unmanned landing missions are planned with the purpose of exploring the physical and biological properties of these near-Earth planets. The capsule entering the Martian or Cytherean atmosphere will provide unparalleled opportunity for "in situ" experimentation. This paper addresses itself to the design of a Mars capsule capable of a safe entry and landing on Mars. Quite simple sensors of pressure, temperature, density, molecular weight, and gross composition of the atmosphere can yield significant physical and ecological data. The safe landing will permit the execution of significant biological experiments for the detection of life.

Data transmitted at a rate of 1 bit/second during the capsule descent and following the landing are best handled by a direct planet-to-Earth communication link. The significance of the experiments and the techniques required are discussed.

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INTRODUCTION

Instrumented entry capsules capable of making measurements both during descent through the Martian atmosphere and after landing on the surface will be essential in man's approach to a detailed study of Mars. Present knowledge derives mainly from observations and measurements made by instruments mounted on a spinning *fly-by* platform, the planet Earth; the miss distance in this case is about 10^8 km. Artificial spacecraft, on a much closer fly-by trajectory, will necessarily sacrifice complexity and refinement of instruments in exchange for the increased angular size presented by the planet and for the freedom from interference of the Earth's atmosphere. This trade-off of instrument complexity to gain proximity to the target is a favorable one, and much can be learned from a vehicle that passes very close to a planet. The recent success of the Mariner II (1962 Aρ1) Venus fly-by demonstrates this well, and fly-by experiments should also be performed on Mars. However, even closer approaches are desirable: Altitude profiles of pressure, temperature, and composition can be determined more accurately from a probe that actually penetrates the planetary atmosphere. Proof of the existence or nonexistence of living organisms on Mars requires the landing of instruments on the planetary surface. Television pictures from a fly-by spacecraft will not lead to conclusions about life on Mars. This is illustrated by a TIROS television picture (Figure 1) which, even at the achieved 2-km resolution, does not reveal the presence of life on Earth in the geographic area shown, even though this area has been occupied by man for many thousands of years.

For an entry probe, the necessary sacrifice in experimental "elegance" is even more severe than for a fly-by, but the reward is direct contact with the planetary atmosphere and surface. This paper describes a set of relatively simple experiments that could be performed, and shows how the few points of data provided by these experiments could yield much new and hitherto unattainable information.

DELIVERY SYSTEM

The delivery system and the overall mission profile will not be discussed in detail; however, a few comments are appropriate.

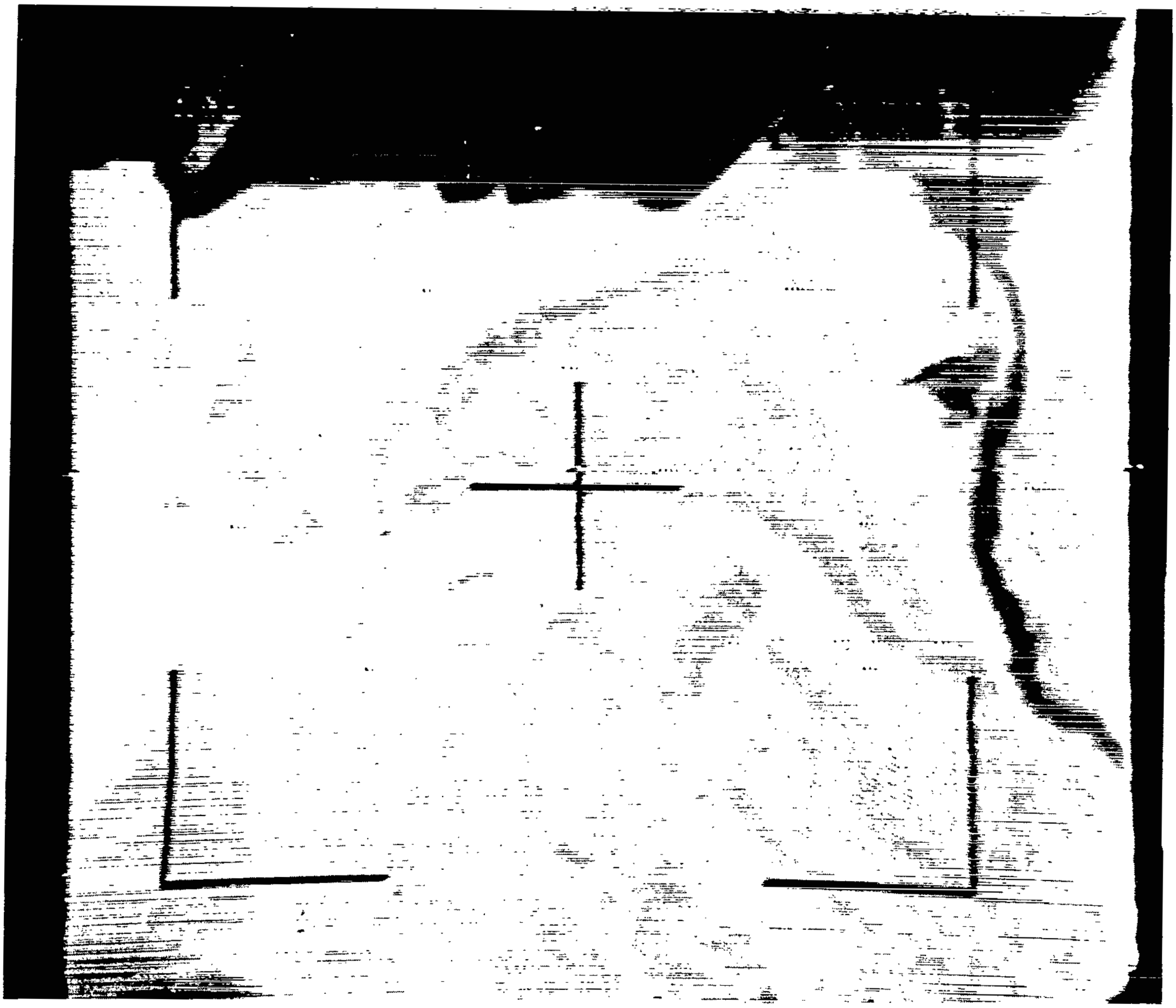

Figure 1—TIROS picture of the Nile Delta and surroundings.

Current spacecraft propulsion and guidance technology can achieve Earth-to-Mars transfers of payloads in the 100-pound class by taking advantage of the relatively close approaches made by Mars as it goes through its oppositions each 26 months. Both the transfer time from Earth-launch to Mars-encounter and the communication distance from Earth to Mars on the date of encounter are variable from one opportunity to the next; typical values are 6 months travel time and 200×10^6 km separation at encounter. Capsule-to-planet approach velocity cannot be controlled; that is, spacecraft weight limitations preclude propulsive (retrorocket) braking. Thus the actual atmospheric entry velocity, representing the combined effects of orbital approach velocity and Mars' gravitational attraction, will be in the neighborhood of 7 km/sec.

The deceleration and heating that a planetary capsule experiences during atmospheric entry at these velocities will require special attention. Fortunately, the technique of high-speed entry has been advanced extensively in the last year or two. Theoretical investigation, shock tube tests, and actual flight experience — such as in the NERV program and the military programs — demonstrate that survival of a small capsule entering the Martian atmosphere is well within present capabilities. The importance of the problem should not, however, be minimized; on the contrary, the entry is recognized as a critical link in the chain of events necessary for a successful landing mission.

All events not absolutely necessary should be removed from in-line positions. Interplanetary experiments, for example, should not be attempted if their functioning or failure could interfere in any way with the primary objective of making planetary entry and landing experiments.

The principle of minimizing the number of in-line events leads to the preference of a direct communication link between capsule and Earth rather than an indirect link that would relay the signal by way of the spacecraft bus.

Hybrid missions that would land a capsule and, at the same time, attempt to use the delivery bus as a fly-by are more complex and might be avoided — at least for the early Mars attempts — in the interest of maintaining simplicity and therefore inherently higher reliability.

We shall assume that spacecraft and capsule both follow an impact trajectory, the capsule being separated a day or so before impact; the spacecraft, now without further function, is allowed to enter and disintegrate in the Mars atmosphere. This of course will require the spacecraft, as well as the capsule itself, to be fully sterilized to avoid the danger of contaminating Mars with Earth-type life forms.

The capsule, having the familiar hemisphere-cone shape and including heat shield and parachute, will weigh approximately 125 pounds. When the shielded capsule has entered the Martian atmosphere, a parachute is deployed, the capsule shielding is dropped, and the periodic measurements of atmospheric pressure, temperature, composition, and scattering of light are transmitted from the capsule directly to Earth until the capsule touches the Martian surface (see Figure 2). These readings can be stored in a memory for subsequent retransmission to Earth.

After landing is completed and the capsule has come to rest in an upright position, measurements of these same quantities are resumed and a biochemical growth experiment is initiated to search for Martian life forms. The measurements are made and transmitted to Earth at regular intervals until sunset on Mars. Sufficient battery energy remains to maintain the capsule temperature at a satisfactory value throughout the Martian night and to permit several transmissions on the following day.

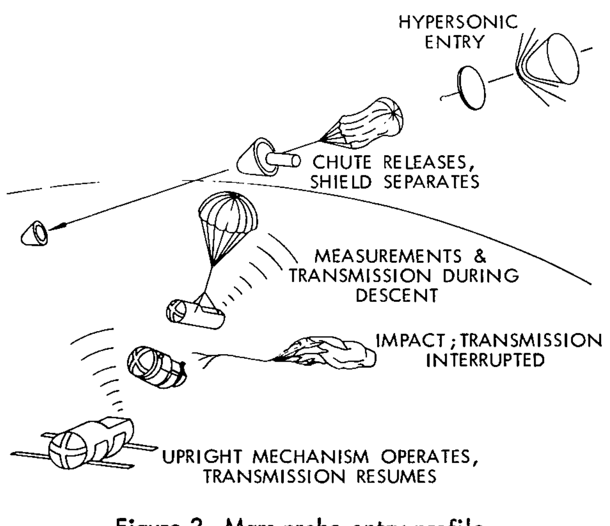

Figure 2—Mars probe entry profile.

EXPERIMENTS

It is appropriate to mention that the purpose here is to describe a set of experiments which might be suitable for Mars entry capsules and that this paper is not addressed to any particular mission or program. The descriptions, although presented in the *indicative mood* for ease of expression, should not be interpreted as representing a final selection of experiments for a specific Mars mission.

The measurements during parachute descent through the Martian atmosphere will determine: (1) the atmospheric temperature, pressure, and density altitude profiles of the Martian atmosphere; (2) altitude profiles of the attenuation and of the scattering of sunlight in the blue, ultraviolet, and near-infrared regions by haze, dust, and clouds; (3) the daylight altitude profiles of the CO_2, H_2O, O_3, N_2, and A content of the atmosphere; and (4) the mean-molecular-mass altitude profile of the atmosphere. The maximum altitude of all profiles will be somewhere in the region of 2.5 to 26 km, depending on the Martian atmosphere's density altitude profile, which in turn will control the function height of the automatic mechanism deploying the parachute and initiating the experiments. On the surface of Mars, measurements will continue throughout the Martian day to determine: (5) atmospheric pressure and temperature; (6) the amounts of blue, ultraviolet, and infrared radiation arriving at the surface directly from the Sun; (7) the amounts of scattering in the blue, ultraviolet, and infrared regions produced by molecules and suspended particles; (8) the attenuation of incoming radiation in absorption bands associated with CO_2, H_2O, and O_3 for varying optical thicknesses of the atmosphere; and (9) the amount of CO_2 metabolically generated by microorganisms that may have been collected into the incubation chamber of the biological experiment.

Some of these determinations (e.g., temperature and pressure) will be made by direct measurements obtained from appropriate sensors; others (e.g., mean molecular mass) will be derived from sensors that measure related quantities, such as velocity of sound and acoustic impedance. Additional sensors are provided to make the engineering and housekeeping measurements (e.g., solar aspect and various instrument temperatures) that are needed for proper calibration and interpretation of the basic experiments. A complete list of the sensors, and the symbols used to represent their outputs, is presented as Table 1. Discussion of the experiments and descriptions of the sensors follow, in the order given in the table.

Pressure

The two pressure sensors are absolute-pressure aneroid potentiometer gages with full-scale ranges of 65 and 200 mb. The gage openings are on the side of the cylindrical instrumentation capsule.

Temperature

Air temperature will be measured over two different ranges by essentially duplicate instruments. The temperature sensors consist of platinum resistance elements mounted on the side of the cylindrical capsule. Ranges from 180° to 300°K and 150° to 320°K are planned.

Table 1

Sensors and Symbols.

Sensor	Symbol
1. Atmospheric pressure, 0 - 65 mb	P_1
2. Atmospheric pressure, 0 - 200 mb	P_2
3. Atmospheric temperature, 180° - 300°K	T_1
4. Atmospheric temperature, 150° - 320°K	T_2
5. Local velocity of sound	c
6. Acoustical impedance of Martian air	z
7. Ultraviolet extinction in an O_3 band (2π ster)	UV_1
8. Ultraviolet extinction in a reference window (2π ster)	UV_2
9. Direct solar radiation in the reference window (collimated sun only)	UV_3
10. Infrared extinction in a CO_2 band (2π ster)	IR_1
11. Infrared extinction in an H_2O band (2π ster)	IR_2
12. Infrared extinction in a reference window (2π ster)	IR_3
13. Direct solar radiation in the reference window (collimated sun only)	IR_4
14. Solar zenith angle with respect to the capsule (along longitudinal axis of capsule)	S_x
15. Solar zenith angle with respect to the capsule (along lateral axis of capsule)	S_y
16. Probe inclination after landing (along longitudinal axis of capsule)	I_x
17. Probe inclination after landing (along lateral axis of capsule)	I_y
18. Temperature of the acoustic instrument (47°C)	T_3
19. Temperature of the infrared detectors (27°C)	T_4
20. Background count rate, biochemical experiment	L_0
21. Count rate, biochemical experiment	L_1
22. Temperature of biochemical instrument and batteries	T_5
23. Battery voltage, and biochemical experiment confirmation	E

Molecular Mass, Density, and Specific Heat Ratio

The mean molecular mass $\bar{M}$, the density ρ, and the mean specific heat ratio $\bar{\gamma} = C_p/C_v$ will be determined by acoustical means. The velocity of sound c in a gas is given by

$$c^2 = \frac{\bar{\gamma}RT}{\bar{M}},$$

where R is the gas constant. This well-known relation has been used in the past in various instrumental techniques to measure the temperature of the Earth's atmosphere by determining c, where $\bar{M}$ and $\bar{\gamma}$ are well known. It is proposed here to reverse this method and to bring a volume of the Martian atmosphere into a thermostatically controlled tube and then to measure $\bar{M}/\bar{\gamma}$ by determining c, where the temperature is well known. Simultaneously, the acoustical impedance $z = \rho_1 c$ of the gas will be measured in the tube, which yields the density ρ_1 of the gas in the tube. From ρ_1 the density of the ambient gas ρ is obtained by the equation

$$\rho = \frac{\rho_1 T_3}{T_1},$$

where T_3 denotes the absolute temperature of the thermostatically controlled tube and T_1 the ambient air temperature measured by the resistance thermometer.

Knowing the ambient air density and temperatures, we arrive at the mean molecular mass by applying the gas law:

$$\bar{M} = \frac{\rho RT}{P} = \frac{zT_3 R}{cP}.$$

Since $\bar{M}/\bar{\gamma}$ has been obtained by the velocity measure, $\bar{\gamma}$ can now be determined.

Figure 3 shows $\bar{M}$ versus $\bar{\gamma}$ for a mixture of the three gases N_2, CO_2, and A. It is generally accepted today that these gases are the major constituents of the Martian atmosphere. The $\bar{M}/\bar{\gamma}$ point of an arbitrary mixture of these gases must fall within the triangle shown. Only the lower part of the triangle need be considered here, since the amounts of CO_2 and A probably will be relatively small compared with the amount of N_2. According to present estimates, the amounts of water vapor, O_2, and O_3 are too small to contribute appreciably to $\bar{M}$; however, a refined analysis will incorporate these components also. Curves of constant c^2 are straight lines through the origin (because c^2 is proportional to γ/M at constant temperature). The relative abundances of the respective components in the three-gas mixture can thus be completely determined by a c and an $\bar{M}$ measurement. The CO_2 concentration found by the acoustical method, although not as accurate as the one derived by the optical means described below, is a most desirable and independent check. Also, the acoustical measurement works equally well in the presence of clouds. In conjunction with a successful optical CO_2 determination, the acoustical experiment will provide a conclusive test of the hypothesis that the Martian atmosphere consists mainly of nitrogen, carbon dioxide, and argon.

The proposed technique, as shown in Figure 4, measures the velocity of sound of a sample of the Martian atmosphere contained in a tube wound in a spiral form of about 1 meter in length and 0.5 cm diameter. For ease in illustration, however, Figure 4 shows a linear arrangement of this tube. At one end of the tube, a generator drives a small sonic transducer at a frequency of about 4 kc. Two identical condenser microphones are separated by approximately 9 wavelengths. Both microphones form part of the tube wall. The acoustic tube is extended beyond the second microphone and is terminated by damping material which, in conjunction with rough wall surfaces, avoids acoustic reflections and standing waves in the tube. The phase shift, measured by the phase comparator, is determined solely by the wavelength of sound in the tube and, since the generator frequency is constant, by the propagation velocity.

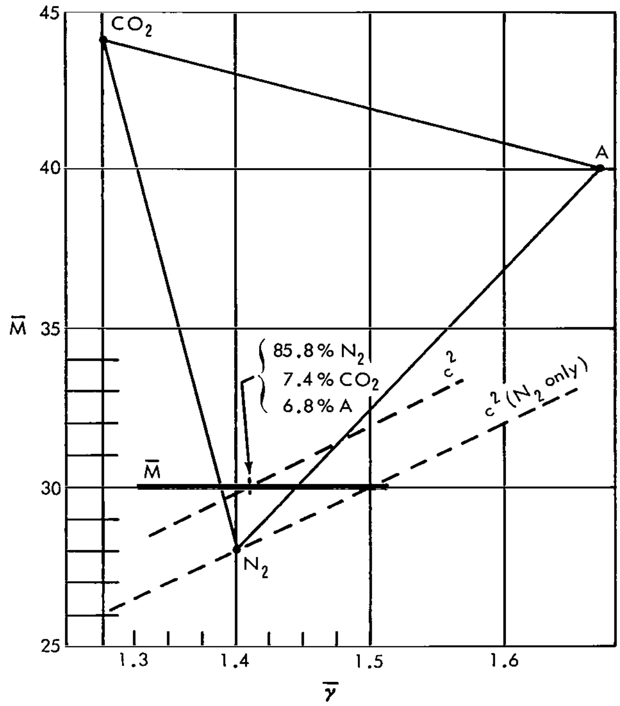

Figure 3—$\bar{M}$ versus $\bar{\gamma}$ for a three-gas mixture.

In addition to determining the speed of sound, the instrument is capable of measuring the density of the gas in the tube. The mechanical and the electrical impedances of the sound generator are chosen so that the velocity of the diaphragm is practically independent of the acoustic radiation impedance of the tube. Under these conditions, the sound pressure developed in the contained gas is proportional to the acoustical impedance. Since the microphones respond to sound pressure, their electrical signals will be proportional to the acoustical impedance of the gaseous medium. The constant of proportionality, which also depends on the transducer sensitivity, is easily determined by calibration in an N_2 atmosphere over the expected pressure range of 20 to 150 mm Hg.

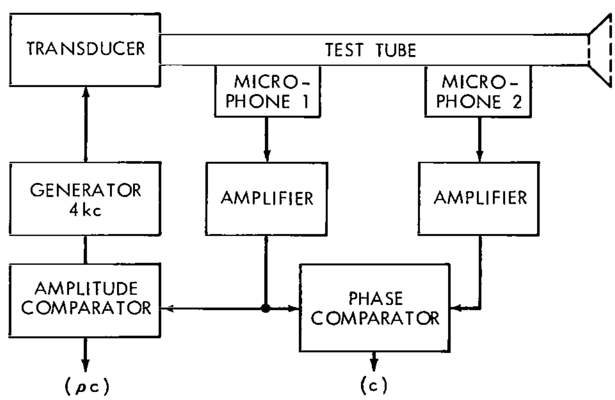

Figure 4—Acoustic experiment.

The accuracy requirements imposed on the speed of sound determination can be judged by considering values shown in Table 2. Values are calculated for a gas temperature of 320°K. The first and last rows of gases represent what are presently considered to be the boundaries for the probable composition of the Martian atmosphere. The instrument is designed to cover the range from about

347 to 365 m/sec. The two microphones, 9 wavelengths apart, register phase differences between 0 and 180 degrees over the 18 m/sec change in sound velocity. A ± 1 percent error in the phase measurements yields the velocity of sound to ± 0.2 m/sec, or an overall error of ± 0.05 percent.

Calculation of the velocity of sound in Table 2 was based on the ideal gas law. It would be more accurate to use Van der Waal's equation, but it can be shown that a change occurs only in the fourth significant figure. Also, the specific heat of gases shows a frequency dependence in the vicinity of molecular relaxation frequencies. This condition is especially true for CO_2 at low pressures and is one of the reasons why a relatively low operating frequency was chosen for the experiment. Because of these conditions, direct calibration is preferred and will be performed by placing the instrument in artificial atmospheres at low pressure for a number of N_2:CO_2:A ratios. An experimental version of the instrument is shown in Figure 5.

Table 2

Velocity of Sound for Various Atmospheric Compositions.

Gas	Velocity of Sound (m/sec)
100% N_2	364
95% N_2 + 5% A	362
95% N_2 + 5% CO_2	358
90% N_2 + 5% CO_2 + 5% A	356
80% N_2 + 10% CO_2 + 10% A	349

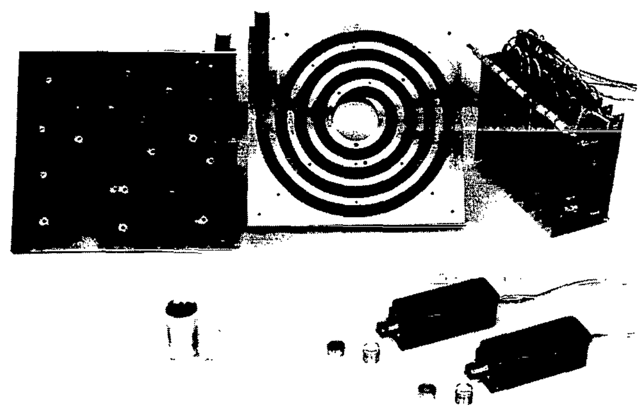

Figure 5—Acoustic experiment hardware.

Atmospheric Composition by Optical Means

The physical basis for the determination of the atmospheric composition by optical means is provided by the extinction of sunlight as it passes through the Martian atmosphere. Quantitatively, the extinction is expressed by

$$I_\lambda = I_{0\lambda} \exp\left(-\tau_\lambda\right) ,$$

where $I_{0\lambda}$ is the intensity of radiation at wavelength λ incident on a column of gas and I_λ the intensity emerging from the gas at the optical thickness τ, where τ is given by:

$$\tau_\lambda = \int_x^0 n(x)\, \delta_\lambda \, dx .$$

The path length traversed in the gas, given by x, is the product of the concentration of the particles producing the absorption and their extinction cross section. If the rate I/I_0 is measured, and if x and δ_λ are known, then the concentration of particles $n(x)$ may be computed.

The total absorption produced by the individual constituents may be computed for various conditions (pressure and temperature) in selected wavelength regions with experimentally determined extinction coefficients.

The O_3 measurement can be best performed in the ultraviolet portion of the spectrum, while the CO_2 and H_2O measurements are better suited to the near-infrared spectral region. The proposed instrumentation will be described under the separate headings of ultraviolet and infrared experiments because of the difference in the required instrumentation for the respective spectral regions.

Ultraviolet Experiments

Extinction Experiments

The ozone content is studied in terms of absorption of solar radiation in the Hartley band region. A 200A bandwidth at about 2800A serves the purpose well.

If Johnson's data (Reference 1) for the solar spectral irradiance in these regions are converted from Earth distance to Mars distance, and conservative estimates of energy losses through the optical system are made, a sufficient amount of energy is found to be available so that standard, readily available photomultipliers and filters may be used for the measurements. Hence, with the Sun as the source, a small (1.5-cm radius) opalescent diffusing hemisphere with a field of view of 2π steradians will collect the solar energy flux and uniformly illuminate (regardless of solar elevation) a small aperture at the center of its base, where a filter will transmit only the energy in the desired spectral region to the photomultiplier. The arrangement is depicted schematically in Figure 6.

Regarding the detector response, only a small reduction in solar radiation is expected in the transmission window at the reference wavelength (3500A) because of extinction in a clear atmosphere, so that a linear response is preferred for the reference channel. A logarithmic response is used for the ozone channel, where large changes in intensity may be anticipated because of the large absorption coefficients.

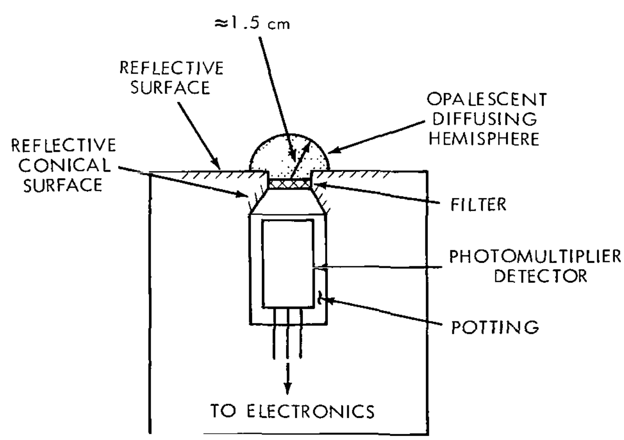

Figure 6—Ultraviolet detector.

Ultraviolet Scattering Measurements

Observed clouds and haze are important factors in the Martian atmosphere, especially in

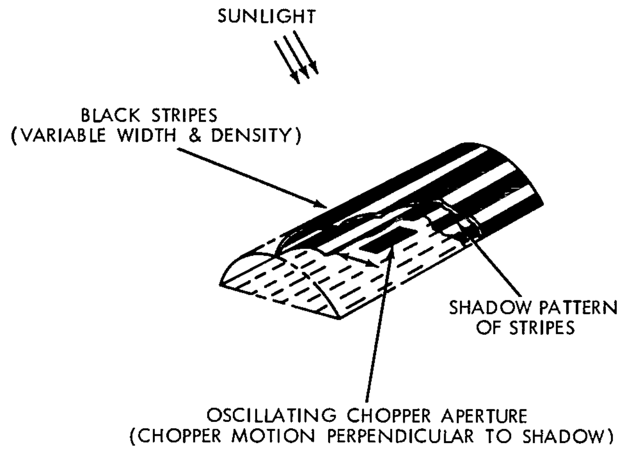

Figure 7—Scattering sensor.

the ultraviolet. The existence of the blue haze, for example, will modify the O_3 estimates and must be taken into account. In itself, the altitude determination of the blue haze (if present at the time) will be a valuable experiment.

Direct solar radiation and scattered skylight are measured by a simple *space chopping* technique. The essential part of the instrument is a transparent shell in the form of a half-cylinder painted in a zebra-like fashion with black stripes parallel to the longitudinal axis (see Figure 7). In direct sunlight, the black stripes cast a sharp shadow pattern on the horizontal plane through the cylinder axis. However, if a portion of the incident sunlight has been scattered by molecules, haze, or dust, the shadows are not completely black. An oscillating aperture, vibrating perpendicularly to the shadow pattern, channels the radiation signal to the detector. If there is no atmospheric scattering, the output of the detector has a peak-to-peak amplitude proportional to the intensity of the direct sunlight appearing between the shadows. Large detector output is thus obtained when there is primarily direct sunlight and little scattering, and hence high pattern contrast. But, when there is only scattered light incident on the cylinder, the shadow pattern is completely destroyed, and no output signal will be developed. The output of the detector is thus proportional to the amount of unscattered sunlight. This measurement is made at 3500A, and a comparison of the results with the UV_3 measurement of the total amount (2π ster) of light in the 3500A reference channel enables us to determine the total scattering produced by the atmosphere in this spectral region.

Infrared Experiments

Extinction Measurements

The measurements in the near-infrared region of the spectrum are similar in principle to those described for the ultraviolet region. Calculations show that the CO_2 content can be inferred from attenuation in its 1.6-micron absorption band. The H_2O content is somewhat more difficult because of the blending of its bands with certain CO_2 bands. However, a several hundred angstrom bandwidth near 1.87 microns (avoiding the strong 2.0-micron band of CO_2) is adequate. Both the H_2O extinction and the CO_2 extinction will be measured with respect to the attenuation in a reference window near 1.7 microns.

Figure 8 shows the total absorption produced by CO_2 and H_2O in the near-infrared region, using present estimates of these constituents and Howard's data (Reference 2) referring to an atmospheric pressure of 42 mb. As with the ultraviolet experiments, the detectors will not require alignment to the Sun, because they are provided with a 2π steradian field of view. Since the expected total amount

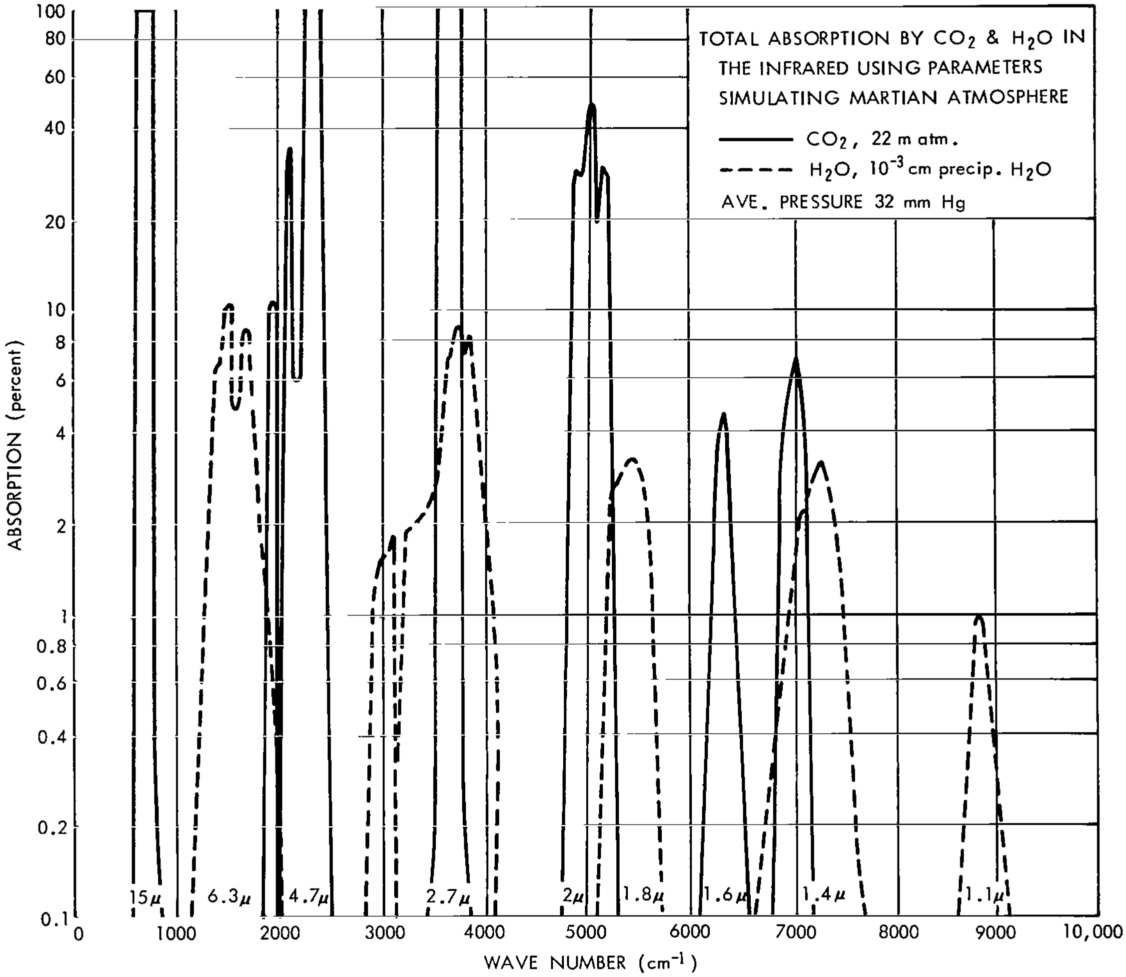

Figure 8—Atmospheric infrared absorption.

of absorption is small, it is preferable to measure directly the intensity difference between the reference channel and each of the spectral bands chosen for the extinction measurements. The instrumentation is outlined schematically in Figure 9.

As shown in Figure 9, the vibrating chopper alternately exposes the detector to the intensities I_1 and I_2, where I_1 is the intensity in the reference window and I_2 the intensity in a spectral band of CO_2 or H_2O. Hence, the intensity difference $I_1 - I_2$ will be measured for both CO_2 and H_2O; and, in addition, the reference window intensity I_1 will itself be measured using the same configuration, simply by blocking

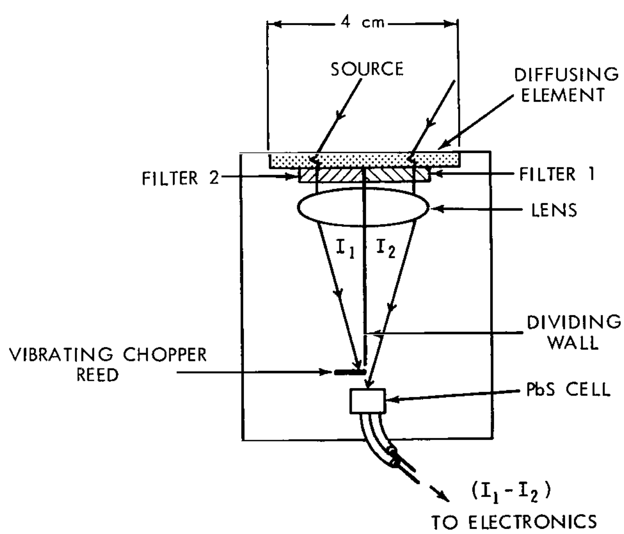

Figure 9—Infrared detector.

out I_2. Lead sulfide is best suited as the detector for this spectral region, although its temperature must be controlled if optimum reliability and stability are to be achieved.

Infrared Scattering Measurements

An experiment to determine the scattering power of the Martian atmosphere in the near-infrared region will also be included. By combining these data with the information obtained from the scattering results in the ultraviolet portion of the spectrum, considerable insight can be gained concerning the nature of the scattering processes and the sizes of haze, dust, and cloud particles. The infrared detector (PbS) and the ultraviolet detector will be housed together, using the same light collector and chopper shown in Figure 7. Two filters will transmit the spectral regions of interest to the respective detectors.

Biological Experiment

Basic Concept

The concentration of water vapor, oxygen, and the amount of ultraviolet radiation at the surface of Mars are important in considering the environment which living organisms might have to face; but knowledge of these environmental conditions will not suffice to answer the question of the existence of life on Mars. To provide a conclusive answer to this question, a life detection experiment has been incorporated into the proposed capsule design. (It is recognized, of course, that only a positive experimental result would be conclusive.) The particular biological experiment, which has been suggested by Mr. G. Levin of Resources Research, Inc. (Reference 3), already exists in breadboard form and will adapt easily to the proposed capsule.

The Experiment

The experiment depends on measurements to detect metabolically generated CO_2 derived from a nutrient medium mixed with a sample of Martian soil under the assumptions that, if life does exist on Mars, almost any soil sample will contain microorganisms and that the metabolic process of these microorganisms results in the generation of CO_2.

The medium (broth) is carried with the instrument to Mars, where a soil sample is obtained by shooting out sticky strings to which soil particles adhere as the strings are wound back into the culture chamber in the instrument. The medium is tagged with C^{14}, and hence any microorganisms using the medium in their metabolic processes will generate a small amount of $C^{14}O_2$, which can be detected by radioactive methods.

The gases leaving the liquid medium will be collected on a thin absorbent-impregnated window above the culture chamber. Immediately behind this window is a solid-state detector that will be used to make periodic counts of the evolved radioactivity. The experiment will show radioactivity and, hence, gas evolved as a function of time. A resultant curve showing an initial lag period followed by the characteristic exponential growth phase and population plateau would constitute evidence for the presence of life. Confirmation of the metabolic origin of the evolved gas would be accomplished by the injection of an anti-metabolite into the culture and the observance of a consequent diminution or cessation in the evolution of gas.

Supplementary Measurements

The solar zenith angle must be known at the time of the extinction measurements to interpret the data properly. This measurement will also help to determine the latitude and longitude of the capsule landing site, for which two instruments are necessary. The first is an inclinometer to determine the probe's attitude with respect to the local vertical. The second instrument determines the solar angle with respect to the probe's fixed coordinate system. By determining the solar zenith angle at regular time intervals, and combining these data with measurements of the solar azimuth, the position of the probe can be determined in terms of Martian latitude and longitude.

The aspect of the Sun will be determined by a passive device employing gray coded light masks and photocells to yield a digital indication of the solar aspect. The sensor is made up of two identical rectangular glass recticles perpendicular to each other. Each recticle contains a thin slit on the top and a 7-bit gray coded pattern on the underside. Seven corresponding photoconductive strips are located under the gray coded masks.

The inclinometer is essentially a set of two pendulums placed at right angles to each other. The shaft of each pendulum positions the slider of a low-friction potentiometer, which in turn generates the desired signal voltage proportional to the position angle of the pendulum. The small unit is hermetically sealed and is designed to operate within the limits of ± 60 degrees from the vertical with an accuracy of ± 2 degrees.

Altitude Measurement

Two methods are used to measure the altitude of the instrument during parachute descent. The first one is based on integration of the hydrostatic equation:

$$dp = -\rho g \, dh ,$$

and consequently

$$h = -\int_{p_0}^{p} \frac{dp}{\rho g} .$$

The second method for obtaining capsule altitude is based on the known terminal velocity, which can be determined in terms of the "weight" and the coefficient of drag of the capsule and parachute.

Integrating over the terminal velocity region yields

$$h = \int_{t_0}^{t} \left[\frac{2\,mg}{\rho C_D A}\right]^{1/2} dt \; .$$

The change in g with altitude, small to begin with, may be handled by an iteration process. The computation of altitude does not require capsule survival, but surface impact time must be known to establish the zero level of the altitude scale.

TELEMETRY

Data transmission from planetary distances requires high efficiency in the transmitting system and low noise in the receiving system in order to minimize payload weight and battery power requirements. The capsule transmitter will operate in the space telemetry band at 2300 Mc, where low system noise temperatures (50°K) are achieved in receiving installations. The relatively few measurements to be transmitted in the available time leads us to trade bandwidth against time; however, the problem of building physical equipment with the required properties indicates practical lower limits of information bandwidth below which no favorable trade-off is achieved. Doppler frequency shift interferes with the acquiring and frequency tracking of extremely narrow bandwidth signals. The major source of Doppler shift will be the relative motion between Earth and Mars, and it can be predicted quite accurately; however, the Doppler shift associated with Mars' axial rotation depends on the location of the landing site. This location will be unknown at the time when the signal is to be acquired; and, as a consequence, a residual frequency uncertainty of approximately 1500 cps will remain. Also affecting the bandwidth versus time trade-off is the achievable crystal stability. Granting this effect the same band uncertainty as the Doppler shift, a crystal stability of 5 parts in 10^7 is needed. Fortunately, once the signal has been acquired, the rate of frequency tracking achievable in such narrow-band receivers is compatible with the maximum rate of Doppler change due to Martian spin (0.06 cps/sec).

As may be seen from the discussion of the measurements, 1 bit/sec is entirely adequate for the transmission of data. With Pulse Code Modulation non-return-to-zero, only a 2.5-cps bandwidth would be necessary for processing this signal; on the other hand, since the loop bandwidth of the receivers is much wider, the use of a subcarrier is indicated. Normally, a strong carrier is needed for locking the loop in the receiver; this forces the designer to compromise in his desire to modulate as much power as he can in the information-carrying side band, and only the necessary minimum in the carrier itself. This minimum is given by the 8 to 9 db locking threshold of present-day receivers. The double-side-band suppressed carrier modulation suggested by Costas (Reference 4), combined with phase-locked loop techniques, eliminates this disadvantage. Costas' technique reconstructs the carrier by making use of the coherence in the two side bands. When such a detector is part of a phase-locked loop, locking is achieved at the reconstructed carrier. Phase modulation in the transmitter can easily be adjusted so that essentially all power lies in the side bands and virtually none in the carrier; thus a receiver as described will lock above threshold and produce an output. If we choose a subcarrier coherent with both the main carrier and the bit generator, the output of the first demodulator is known in its frequency — regardless of Doppler shift — and can be filtered optimally. Table 3 shows a set of calculated system parameters.

The calculation assumes a capsule antenna pattern such that 0-db gain can be achieved at all resting positions on the Martian ground and for all polarization. Obviously, a null must exist tangentially to the surface, and a design objective of linear polarization at 50 degrees from the vertical is more realistic. The capsule antenna will transmit circularly with a gain of approximately 7 db at the vertical. A slight possibility of an unfavorable resting position of the capsule remains, but the chance appears to be no greater than that of failure in the uprighting mechanism itself.

PCM encoded transmissions, where every single measurement is of importance in the sense that interpolations are virtually impossible to make, need error detection bits in their structure to enhance confidence in the measurement taken. Only small additional redundancy is needed for single-bit error correction and dual-bit error detection in a matrix. This is accomplished by the provision of horizontal and vertical parity checks. A frame consists of 10 words, each of which contains 7 measurement bits plus 1 parity bit. The frames are generated at a 1 bit/sec rate and are organized

Table 3

Data Transmission Link Information.

Parameter	Value
Distance	220×10^6 km
Path attenuation at 2280 Mc	-266.2 db
System noise temperature	50°K
Noise power (bandwidth, 1 cps)	-211.6 dbw
Receiving antenna gain (210-in. diameter)	+61.1 db
1st demodulator noise (bandwidth, 8 cps)	-9.0 db
Bit rate	1 bps
Transmitter mismatch	-1.5 db
Transmitter output	+18.5 dbw (70 watts)
Vehicle antenna gain	0 db
Margin	-5 db
Loss due to spectral power distribution	-1.1 db
S/N at input of subcarrier PCM demodulator in 8 cps	+ 9.5 db - acquisition and locking threshold
2nd demodulator (PCM) (bandwidth, 2.5 cps)	+5 db
S/N of PCM output	14.5 db
Single-bit error probability	$<10^{-3}$

as follows: Word number 1 is the frame tag; bit positions 1 and 2 specify the type of frame, and the remaining 5 data bits specify the number of the frame. The parity bit in position 8 is 1 or 0 so as to make the total number of 1's in the 8 bits odd. Words number 2 through 9 contain the data; the parity bit is made 1 or 0 so as to make the total number of 1's in the word odd or even in a specifically chosen pattern. Word number 10 is the vertical parity checkword, and each bit is made a 1 or 0 so as to make the total number of 1's in its vertical column either even or odd following a similarly prearranged pattern. Synchronism is established by checking for the uniqueness of the parity pattern. Once word and frame synchronization have been established, this structure provides single-bit error correction and dual-bit error detection. The data are transmitted serially by increasing bit number in each word and by ascending word number.

There are three types of frames: A, B, and C. Frame A contains pressure, temperature, and acoustical data and thus is used to provide information during descent — whether by day or night — and after landing. Frame B contains data from the optical experiments and gathers information during descent — if by day — and after landing. Frame C contains data from the biological experiment and from the attitude sensors, and is used only after landing.

The uncertainties involved in communication over planetary distances warrant inclusion of a storage capability in the capsule so that certain transmissions can be repeated. The storage also can be used for recording data taken between data transmission times.

Selected frames of data acquired during descent will be stored and later re-transmitted, along with data taken after landing. If descent occurs during daylight, the data that are simultaneously transmitted and selectively stored in a magnetic core memory will consist of alternate frames of types A and B. If descent occurs during the Martian night, frame A data only will be stored. About 15 minutes after landing, one frame of type C will be acquired and stored. Transmissions will then occur every 2 hours after landing until sunset, and they will be interrupted until 2 hours after sunrise. The batteries provide sufficient energy to power a maximum descent-time transmission, four transmissions of 20 minutes each, the necessary electronics for 24 hours of operation, and heaters needed to survive the low temperatures of the Martian night.

Because of the lack of accurate knowledge of the Martian atmosphere, the descent time can vary widely; and the storage and re-transmission of data must be adjusted so as to assure measurements from at least a few different altitudes. Depending on the density of the Martian atmosphere and entry velocity, the descent time may vary from a minimum of 4 minutes or 3 frames to a maximum of 57 minutes or 42 frames.

During descent, A and B frames are transmitted and stored in four slots of a storage matrix. When the descent time is long enough, the oldest frame is erased and replaced by a new one; this will occur after the fourth frame. The first, however, is stored permanently. To accommodate very long descent times, the tenth frame is stored permanently, and the two remaining slots are filled with the two most recent measurements. The transmission sequence after landing for three different descent times is then:

For minimum descent — 4 minutes, 3 frames acquired:
C-0, B-0, A-0, C-1, A-1, B-1, A-1, B-1, A-2, B-1, C-0, A-0, B-0

For nominal descent — 30 minutes, 22 frames acquired:
C-0, B-0, A-0, C-1, A-1, B-1, A-10, B-10, A-9, B-9, A-11, B-11, C-0, A-0, B-0

For maximum descent — 57 minutes, 42 frames acquired:
C-0, B-0, A-0, C-1, A-1, B-1, A-10, B-10, A-20, B-20, A-21, B-21, C-0, B-0, A-0

If descent occurs in the dark, only A frames are stored.

The proposed power profile requires approximately 800 watt-hours of energy to accomplish the capsule mission. About 23 pounds of individually potted silver-zinc cells providing 40 watt-hours/pound will be used in the pressurized battery package. The battery temperature will be maintained at, or just below, + 10°C during the flight aboard the bus. At this temperature, the loss of capacity is less than 0.2 percent per month, and the need for trickle charging is thus eliminated.

The optimum operating temperature for silver-zinc cells is about 25°C. It is anticipated that entry heating will raise the battery temperature no more than a few degrees above the 10°C storage temperature. Hence a good operating temperature, in the neighborhood of 15°C, may be expected at the start of the parachute descent phase when the capsule measurements and transmissions are initiated.

INTERPRETATION OF RESULTS

Each individual sensor will provide valuable information, but the scientific significance of the overall mission lies in the interrelation of the results, shown in Figure 10. Each sensor contributes information to one of more of blocks representing the important physical properties; these in turn serve as stepping stones to formulate a consistent and detailed picture of the Martian atmosphere. Conclusions that would exceed our present knowledge markedly can be drawn about the general circulation, heat balance, composition of clouds, and even geological history. The block diagram presented here is far from complete. Earth-bound observations, for example, would show up as a third dimension to this network of conclusions. It is important to note that the network is overdetermined — that is, that some parameters, such as the molecular weight, are derived from different sensors independently. This provides both a convenient check of consistency and a form of redundancy. The failure of one or another sensor, therefore, would not be of fatal consequence in interpreting the results, and the determination of various parameters by essentially independent methods will confirm, and even improve, the overall accuracy of the experiments.

CONCLUSIONS

A program to deliver instrumented entry capsules into the atmosphere and thence to the Martian surface to telemeter back a few points of fundamental data is seen as an essential part of man's future approach to a detailed study of Mars: Observations from Earth and from "fly-by" spacecraft — both extremely useful — suffer from the absence of direct contact; entry capsules, although necessarily limited at present to "simple-minded" experiments, can make up for this deficiency.

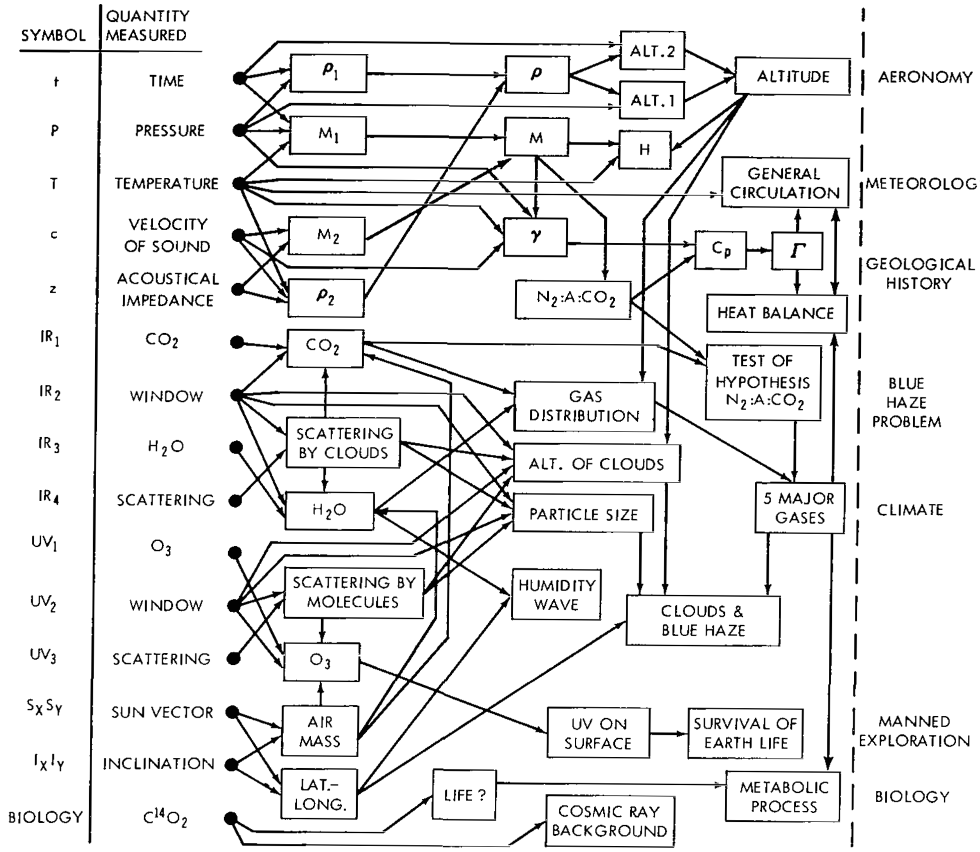

Figure 10—Mars probe, flow diagram of conclusions.

Current technology can deliver a 125-pound capsule containing the necessary heat shield, parachute, and telemetry for 15 pounds of "experiments." A set of interrelated experiments based on obtaining a few data points from each of several sensing devices can provide data on altitude profiles of pressure, temperature, and density; on atmospheric composition and structure through optical scattering and absorption measurements; and on the presence or absence of life forms through a simple test for metabolism in a mixture of a nutrient medium and Martian soil.

Telemetry at 1 bit/second, achievable with a 70-watt capsule transmitter and a 210-foot receiving antenna, will allow real-time transmission during parachute descent and for brief periods subsequent to landing. Storage for delayed transmission will permit a few night-time measurements when the capsule is out of sight from both Sun and Earth. The communication link will transmit both *scientific* information and the supporting *engineering* information (e.g., temperature of sensors, attitude of the instrument package, and location of its landing site).

Mission design stresses *reliability through simplicity.* Only a few basic quantities are measured, but they are selected so that each of several important properties — e.g., composition, nature and altitude of clouds, and habitability to various life forms – can be inferred from more than one combination of the basic measurements. This will afford effective cross-checking and a form of redundancy in that none of these important properties is completely dependent on a single sensor for its determination. Similarly, the important properties to be determined are themselves selected so that they can be combined in various ways to yield broad conclusions in the general fields of aeronomy, climatology, geological history, biology, and manned exploration.

Just as the individual data points and the properties inferred from them may be seen as a network of interrelated information leading to a set of general conclusions, so also would a series of Mars entry capsule missions become part of a much larger network contributing to man's knowledge of the universe around him.

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